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When Should We Treat Galaxies as Isolated?

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ABSTRACT

Traditionally, secular evolution is defined as evolution of systems where the internal growth of structure and instabilities dominates the growth via external drivers (e.g. accretion and mergers). Most study has focused on "isolated" galaxies, where seed asymmetries may represent realistic cosmological substructure, but subsequent evolution ignores galaxy growth and interactions. Large-scale modes in the disk then grow on a timescale of order a disk rotation period ($\sim 0.1-1\,$Gyr). If, however, galaxies evolve cosmologically on a shorter timescale, then it may not be appropriate to consider them "isolated." We outline simple scalings to ask whether, under realistic conditions, the timescale for secular evolution is shorter than the timescale for cosmological accretion and mergers. We show that this is the case in a relatively narrow, but important range of perturbation amplitudes corresponding to substructure or mode/bar fractional amplitudes $\delta \sim 0.01-0.1$, the range of most interest for observed strong bars and most pseudobulges. At smaller amplitudes $\delta \ll 0.1$, systems are not isolated: typical disks will grow by accretion at a comparable level over even a single dynamical time. At larger amplitudes $\delta \gg 0.1$, the evolution is no longer secular; the direct gravitational evolution of the seed substructure swamps the internal disk response. We derive criteria for when disks can be well-approximated as "isolated" as a function of mass, redshift, and disk stability. The relevant parameter space shrinks at higher mass, higher disk stability, and higher-*z* as accretion rates increase. The cosmological rate of galaxy evolution also defines a maximum bar/mode lifetime of practical interest, of $\sim 0.1\,t_{\rm Hubble}(z)$. Longer-lived modes will encounter cosmological effects and will de-couple from their drivers (if they are driven).

Key words: galaxies: formation — galaxies: evolution — galaxies: active — galaxies: spiral — cosmology: theory

1 INTRODUCTION

Isolated disk galaxies are prone to a number of important instabilities that play a major role in shaping observed late-type disk and bulge populations, with the most well-known and well-studied being the traditional bar and spiral instabilities. Both bars and spiral structure are ubiquitous in the local disk population (Marinova & Jogee 2007; Menéndez-Delmestre et al. 2007; Barazza et al. 2008), and their abundance appears comparable at higher redshifts (Sheth et al. 2003, 2008; Jogee et al. 2004). By amplifying small perturbations into coherent, long-lived, large-scale non-axisymmetric modes, these structures enable disks to evolve significantly – re-distributing material in angular momentum and phase space – in a few orbital periods. As a consequence, observations and simulations indicate that these structures are important in shaping the cosmological evolution of disk sizes, scale heights, and the abundance, structural properties, and mass fraction in "pseudobulges" (disk-like bulges that result from angular momentum exchange in these modes), a population increasingly prominent in low-mass and later-type disk galaxies (e.g. Debattista et al. 2004; Kormendy & Kennicutt 2004; Weinzirl et al. 2009).

Traditionally, the growth and evolution of these *global* modes is referred to as "secular" evolution: by definition, evolution that is slow relative to the local dynamical time. This contrasts with violent relaxation – seen in e.g. galaxy-galaxy major mergers – in which the potential fluctuates on short timescales, and *local* instabilities, involving e.g. clumping, star formation, and formation of bars on small scales (sub-kpc).

As a consequence, the secular evolutionary channel has, for the most part, been studied in the context of isolated galaxies. Given an isolated, self-gravitating stellar (or stellar+gas) disk that meets certain instability criteria, small non-zero amplitude in the large-scale modes that identify morphological bar and spiral patterns (characteristic wavelength of order the disk length) will grow exponentially on a timescale of a few orbital periods (see e.g. the discussion in Binney & Tremaine 1987). The evo-

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lution and dynamics of these modes have been well-studied in idealized cases of isolated disks with properties similar to the Milky Way, but by design bar or spiral wave-unstable (Schwarz 1981; Athanassoula et al. 1983; Pfenniger 1984; Weinberg 1985; Combes et al. 1990; Hernquist & Weinberg 1992a; Friedli & Benz 1993; Athanassoula 2002a; Athanassoula & Misiriotis 2002; Athanassoula 2002b; Weinberg & Katz 2007b; Kaufmann et al. 2007; Patsis & Athanassoula 2000; Mayer & Wadsley 2004; Berentzen et al. 2003, 2004; Foyle et al. 2008). In particular this informed study of the role of secular evolution in shaping galaxy sizes, dynamics, and morphology.

However, in ΛCDM cosmologies, structure grows via continuous accretion and mergers. Although major mergers are rare, both theoretical calculations and observations suggest that minor mergers are ubiquitous, and accretion of new cold gas is rapid in low-mass galaxies (Woods et al. 2006; Maller et al. 2006; Barton et al. 2007; Woods & Geller 2007; Stewart et al. 2008b). Together with the typical substructure present in ΛCDM halos (Taylor & Babul 2004; Gao et al. 2004), this suggests the concern that there may not be in practice such a thing as an "isolated" galaxy at the level of interest.

More recent studies of secular evolution have therefore focused on more realistic scenarios, exploiting merger histories from cosmological simulations in semi-idealized studies of single galaxies (Bournaud & Combes 2002; Benson et al. 2004; Gauthier et al. 2006; Berentzen & Shlosman 2006; Kaufmann et al. 2007; Curir et al. 2007; Kazantzidis et al. 2008; Romano-Diaz et al. 2008). These simulations again reveal bars and spiral structure to be prominent – arguably more so than in isolated simulations – but it is less clear whether their formation and evoluton can be attributed to the same secular processes at work in isolated systems, or whether they are driven systems owing to substructure and accretion in the galaxy disk and halo.

The important question for models is: can any galaxy in a realistic cosmological context still be approximated as "isolated" for certain purposes? If so, in what regimes as a function of redshift, galaxy mass, and internal properties is this applicable? What are the corresponding implications for interpretation of bar fractions and lifetimes? And ultimately, what does this imply for the importance of isolated secular evolution in driving the evolution of galaxies and formation of bulges?

In this paper, we attempt to address these questions by means of a simple comparison of cosmological accretion rates and characteristic timescales for secular evolution. This approach allows us to identify the regimes where galaxies can be safely considered "isolated" versus where cosmological effects may not be negligible. We show that there is an interesting regime of secular modes with fractional mass/amplitude ~ 0.1 where the secular growth mode dominates and the isolated galaxy approximation is good (§ 2). We show how this scales with galaxy mass, redshift, and disk stability properties (§ 3), and identify some basic consequences for the lifetimes of large-scale modes in disks (§ 4). Our goal is not a definitive description of secular evolution, but rather to provide a set of simple initial constraints to provide context for more detailed studies of the interesting parameter space.

Throughout, we adopt an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ cosmology, but our conclusions are not sensitive to the choice within the range allowed by present observations (e.g. Komatsu et al. 2009).

2 SECULAR EVOLUTION VERSUS COSMOLOGICAL EVOLUTION

Consider an "initial" equilibrium, axisymmetric disk+halo system at time $t = 0$. In this limit the system will not evolve any non-axisymmtric modes. Therefore, introduce a non-axisymmetric perturbation to the disk potential of amplitude

$$\delta_0 \equiv \frac{\delta\phi}{\phi}\ . \tag{1}$$

We are specifically interested in *global* models, so $\phi \sim GM/R$ is the potential of interest (where M is the disk+enclosed halo mass and R is a characteristic effective radius/scale length). The precise meaning of the perturbation $\delta\phi$ differs depending on the mode(s) of interest and configuration. For example, in idealized N-body simulations, this typically corresponds to shot noise. However, in realistic cosmological settings this will correspond to substructure in the disk or halo, with $\delta\phi \sim Gm/r$ (where m is the substructure mass and r its "initial" distance). The relevant numerical prefactor will depend on the orbit, phase-space structure, and mode (for example, for a bar, the desired quantity is the time-averaged contribution to the $m = 2$ mode at radius $\sim R$ in the co-rotating frame); for our purposes, the scaling (not absolute value) of δ is most important.

At early times (before saturation), this non-axisymmetric term will be amplified internally and grow roughly exponentially:

$$\delta(t) = \delta_0\, \exp(t/t_0) \tag{2}$$

where t_0 is the effective secular timescale, which is typical of order a few orbital times (again, this is for global modes, not local; see e.g. Holley-Bockelmann et al. 2005; Weinberg & Katz 2007a,b). This growth time has been the focus of considerable study, and is one of the many important results of isolated disk studies. For example, for a disk bar in a strongly unstable bulge-free Milky Way-like disk, Dubinski et al. (2008) show Equation (2) is a good approximation to the behavior in simulations, with $t_0 = 8\pi/\kappa \approx 2.83\,P_d$ (where κ is the epicyclic frequency, $= 2^{3/2}\pi\,P_d^{-1}$ for a constant circular velocity disk, and $P_d = 2\pi\,R/V_c$ is the disk circular period at its effective radius). Klypin et al. (2008) find a similar $t_0 \approx 3-5\,P_d$ for thin, bulge-free MW-like disks (albeit with a much larger $t_0 \sim 10-30\,P_d$ for thick $H/R \gtrsim 0.5$ disks; see also Colín et al. 2006). Martinez-Valpuesta et al. (2006) see timescales from $\sim 2.5-10\,P_d$, depending on whether the bar growing is an initial mode or a secondary (post-buckling) mode. A similar range of timescales is found (with considerable galaxy-to-galaxy variation) in live cosmological halos in Berentzen & Shlosman (2006).

For less cosmologically motivated, but more general and analytically tractable disk mass profiles, Athanassoula & Sellwood (1986) find typical $t_0 \sim 1.0-6.7\,P_d$ for realistic halo mass fractions $\sim 1/4-1/2$ (fraction of the total mass owing to the halo at $< R$) and scale heights $H/R \sim 0.1$. Narayan et al. (1987) and Shu et al. (1990) obtain $t_0 \sim 0.8-1\,P_d$ for gas disks with an outer Lindblad resonance at $R \gtrsim R_e$ (of interest for global modes here) and no halo.

More stable systems will evolve more slowly; for the sake of generality we define

$$t_0 = N_{\rm Disk\ Periods} \times P_{\rm d} \equiv \frac{1}{1-\chi_{\rm eff}}\,P_{\rm d} \tag{3}$$

where $\chi_{\rm eff}$ is an effective stability parameter: $\chi_{\rm eff} \sim 0$ represents typical, cosmologically realistic disks maximally unstable to large-scale modes, which will evolve on a single orbital time; and $\chi_{\rm eff} > 1$ systems are stable and experience only oscillations, rather than

amplifying modes.[1] Note that, formally speaking, $\chi_{\rm eff} < 0$ is allowed. For certain bar configurations, for example, $t_0 \sim 0.7\,P_d$ has been obtained (see e.g. Adams et al. 1989; Earn & Sellwood 1995), or even, for spiral structure in the weak winding approximation, $t_0 \sim 0.4\,P_d$ (Toomre 1981). However, those situations all involve no halo and an infinitely thin disk, and somewhat different matter profiles from what are observed in typical disks. For moderate halo contributions or disk thickness, t_0 is unlikely to be smaller than P_d by any but a small factor ($t_0 \sim 0.7-0.8\,P_d$), a small difference relative to the uncertainties in other quantities calculated here. And the MW-like examples above illustrate that $\chi_{\rm eff} \approx 0.5-0.75$ is probably the case of greatest interest for realistic disk plus halo systems, even for strongly unstable systems. To be conservative, however, we will adopt $\chi_{\rm eff} = 0$ for all numerical estimates, unless explicitly otherwise specified.

However, galaxies are not static, and two things will happen that might compete with this internal self-amplification: (1) the substructure itself can dynamically evolve, driving stronger perturbations and/or merging; and (2) new mass of magnitude comparable to the disk mode can be accreted/merge. If either of these occurs on a timescale shorter than t_0 (the effective secular timescale), the system should not be considered “isolated” for purposes of secular evolution.

Consider case (1), the dynamical evolution of the substructure itself. Given some substructure/perturbation of mass fraction δ at some initial radius of interest r, the orbit will decay on a timescale of order the dynamical friction time; correspondingly, the perturbation $\delta \propto \delta\phi \propto r^{-1}$ will grow on the same timescale.[2] Strictly speaking, dynamical friction does not dominate angular momentum loss at small radii; rather, resonant tidal interactions act more efficiently (Barnes & Hernquist 1992). However, properly calibrated, the dynamical friction time is not a bad approximation (e.g. Boylan-Kolchin et al. 2008). For an isothermal sphere or Mestel (1963) (flat rotation curve) disk, this time is simply:

$$t_{\rm df} = \frac{R/V_c}{2\,\beta\,\ln\Lambda}\,\frac{M_{\rm enc}(r)}{m}\,\frac{r}{R} \approx \frac{0.2}{\delta_0\,\ln\Lambda}\,P_{\rm d} \tag{5}$$

where the equality on the right comes from the definitions of δ_0 and P_d.[3] Since we are considering the magnitude of the perturbation relative to the disk, the time here scales with the disk dynamical time at fixed δ_0 (as opposed to e.g. the Hubble time for halo-halo orbital decay at large radii).

The left panel of Figure 1 compares this timescale to the secular evolution timescale t_0. For representative purposes, we assume a “maximally unstable” $t_0 = P_d$ ($\chi_{\rm eff} = 0$) MW-like disk with $P_d = 2\,\pi\times 5\,{\rm kpc}/200\,{\rm km\,s^{-1}} \approx 160\,{\rm Myr}$, and total stellar mass $= 5\times 10^{10}\,M_{\odot}$. This is easily generalized; P_d (at the scale $\sim R$ of the disk itself) appears to be independent of mass in observed disks (e.g. Courteau et al. 2007, and references therein). We plot the results assuming such a disk exists at redshift $z = 1$, but the qualitative scalings are similar at redshift $z = 0$, and we will show the redshift dependence explicitly below. We compare the dynamical friction time $t_{\rm df}$; here we show the results using the full orbital parameter-dependent fits from simulations in Boylan-Kolchin et al. (2008), which allows us to quote the $\pm 1\,\sigma$ range of $t_{\rm df}$ from the range of orbits observed in cosmological simulations (Benson 2005; Khochfar & Burkert 2006). Using the simpler formula in Equation 5 is similar to the median expected.

Comparing Figure 1 or Equations 3 & 5 shows that the dynamical evolution of the perturbation is more rapid than the internal response for mass ratios larger than

$$\delta_{\rm crit,\,df} = \frac{1-\chi_{\rm eff}}{4\,\pi\,\beta\,\ln\Lambda} \sim 0.2\,(1-\chi_{\rm eff})\ . \tag{6}$$

This is ultimately an obvious regime; when $\delta\phi/\phi \sim 1$, direct evolution dominates the potential fluctuations. We denote this the “major merger regime”: in the case where δ corresponds to some substructure, this clearly requires a mass ratio $\mu \gtrsim 0.2$ with $r \sim R_d$, i.e. close passages of major companions. Note though that this does not *have* to be a merger. For example, a sufficiently strong disk fragmentation event will be similar. Physically, this is still dynamically distinct from secular evolution (from e.g. bars, etc.) – it will “look like” a merger inside the disk (see e.g. Elmegreen et al. 2008).

Now consider case (2): new growth/perturbations/mergers. Note that we are no longer considering the evolution of *individual* perturbations, but the time between new perturbations of the same or greater magnitude. If this is $\ll t_0$, then the system is not isolated. A lower limit to this is given by the rate of *baryonic* accretion/merging onto the disk (if accreted systems retain some dark matter, they will represent larger perturbations, but there is at least a lower-limit in the mass added in baryons to explain the disk mass). Detailed analyses of these rates have been discussed extensively in the literature (see e.g. Brown et al. 2007; Guo & White 2008; Wetzel et al. 2009; Genel et al. 2008; Stewart et al. 2008b). Here, we use a simple semi-empirical model to define some of the relevant scalings; for more discussion, see Hopkins et al. (2009a). A variant of the model, based on subhalo-subhalo merger rates, is also described in detail in Hopkins et al. (2008a). Following Stewart et al. (2008a), we begin with dark matter halo merger trees (here from Fakhouri & Ma 2008). Empiri-

[1] Under certain restrictive circumstances, our $\chi_{\rm eff}$ here is analogous to the Toomre Q or X parameter $X \equiv \kappa^2\,R/(2\,\pi\,n\,G\,\Sigma)$ or a (renormalized) Ostriker-Peebles criterion (proportional to the ratio of rotational kinetic to potential energy). For e.g. the bar in a two-dimensional Kuz'min disk approximation presented in Athanassoula & Sellwood (1986), we can translate their Equation 3 to obtain

$$\chi_{\rm eff} = 0.3 + 1.1\left(\frac{f_{\rm halo}+f_{\rm bulge}}{1/3}-1\right) + 0.6\left(\sqrt{\frac{H}{0.1\,R}}-1\right)\ , \tag{4}$$

in physical terms of the disk thickness H/R and halo plus bulge (non-disk) mass fraction inside R. The definition in Equation 3 is not, however, meant to represent specific instabilities, but to allow for general large-scale disk modes with a characteristic growth time/stability criterion.

[2] Strictly speaking, realistic cosmological perturbations grow continuously, so an “initial” radius is ambiguous. However, there is still some $\delta\phi$ that scales as described at a given instantaneous r, and this is what ultimately enters into the equations derived. Also, in practice, such modes – where induced by substructure – often appear suddenly (i.e. in a time $< P_d$ when $r \sim R$; this is because at larger radii, the *net* non-axisymmetric $\delta\phi$ contribution is suppressed by a Poisson $\sim N^{-1/2}$ ($\sim R^{-3/2}$) term. In simulations, for example, perturbations are typically dominated by a few close passages of clumps/substructure where $r \sim R$ (although these may be from longer radial orbits; see Velazquez & White 1999; Bournaud & Combes 2002; Gauthier et al. 2006; Kazantzidis et al. 2008; Hopkins et al. 2008b). In any case, since our derivations rely on δ, rather than r explicitly, this is not a large source of uncertainty.

[3] In detail, β is a constant that weakly depends on the mass profile and velocity isotropy: $= 0.428$ for an isotropic isothermal sphere and $= 0.32$ for a thin Mestel (1963) disk averaged over random inclinations (used in Equation 5). The Coulomb logarithm is approximately $\Lambda = 1 + 1/\delta_0$ (Boylan-Kolchin et al. 2008; Jiang et al. 2008). For Figure 1, we use the fitting functions from Boylan-Kolchin et al. (2008), with appropriate eccentricity and orbital parameter dependence, rather than the simplified Equation 5, but the results are similar on average.

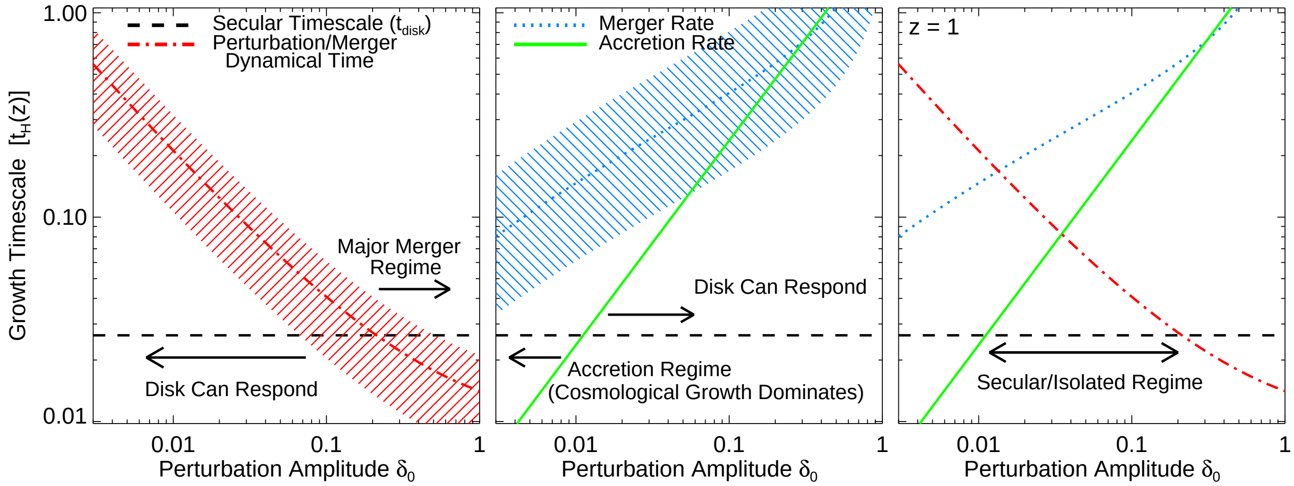

Figure 1. Characteristic timescales for evolution of perturbations in unstable $\sim L_*$ disks (here at $z = 1$, with $\chi_{\rm eff} = 0$). *Left:* Timescale for internal disk response (secular evolution) to amplify some large-scale mode with amplitude δ, compared to the timescale for an individual perturbation to evolve on its own (via e.g. dynamical friction). Analogous to major mergers, direct evolution is more rapid than disk response for major perturbations $\gtrsim 0.2$. Units are the age of the Universe at this redshift. *Center:* Secular timescale versus timescale for the disk to accrete a *new* fractional gas mass $> \delta$ or undergo a *new* merger with mass ratio $> \delta$. At sufficiently low amplitudes, accretion is non-negligible over the secular response timescale. *Right:* All timescales. Disks are effectively *both* isolated and potentially secular evolution-dominated in a regime around $\delta \sim 0.1$. Raising $\chi_{\rm eff}$ will increase the "secular timescale" and decrease this range.

cal halo occupation models and other observations constrain the average galaxy mass per host halo (or subhalo) mass, with little scatter – so at a given instant we simply populate the halos with galaxies. Here assigning stellar mass given the fitted $M_*(M_{\rm halo}\,|\,z)$ from Conroy & Wechsler (2009) and gas mass given the fits to $M_{\rm gas}(M_*\,|\,z)$ from Stewart et al. (2009) (for the observations used in the fits, see references therein and Bell & de Jong 2001; Erb et al. 2006; Fontana et al. 2006; Pérez-González et al. 2008).

The uncertainties in this modeling methodology will be discussed in detail in Hopkins et al. (2009b), but for our purposes they are relatively small (factor ~ 2 uncertainty in the merger rate near $\sim L_*$, owing to a combination of uncertainty in $M_*(M_{\rm halo})$ and the halo-halo merger rate) at $z < 2$, because it is primarily the *shape* of the galaxy-halo mass correlation (rather than e.g. its absolute normalization) that affects galaxy-galaxy merger rates.[4] Note, however, that the uncertainties grow rapidly at higher redshifts, owing to the lack of empirical constraints. Evolving the system forward some small increment in time, we can "add up" the mergers (in detail, we add a dynamical friction "delay" time between each halo-halo merger and subsequent galaxy-galaxy merger, with the formulae from Boylan-Kolchin et al. 2008). This gives merger rates; but also, knowing the new halo mass (after accretion/growth in this time interval), the empirical halo occupation constraints define the "expected" galaxy mass for the updated halo mass. We simply assign whatever galaxy mass growth is needed to match this (not already brought in by mergers) to "accretion." Note that this is a lower limit to the accretion rate, reflecting *net* accretion (outflows may remove mass, requiring more new gas inflow).

The middle panel of Figure 1 shows the relevant timescale for both mergers (median time Δt between mergers with baryonic mass ratio $\mu \equiv M_{\rm bar,\,2}/M_{\rm bar,\,1} > \delta_0$) and accretion ($\Delta t$ for the disk to grow via accretion by a mass fraction $> \delta_0$). Accretion tends to be the dominant growth channel (relative to e.g. minor mergers), for all but the most massive galaxies (where gas accretion is "quenched"). As a result, the time between new mergers may be long, but at sufficiently low δ_0, growth by accretion is more rapid than internal disk response. We denote this the "accretion regime." Again, the behavior is easily understood: if one is interested in evolution at the $\ll 10\%$ level, then galaxies cannot be considered isolated for even a single dynamical time, as they will grow by more than this amount in that time.

The relevant criterion can be roughly estimated as follows: to very crude approximation, fractional galaxy growth rates scale as $\sim \alpha/t_{\rm Hubble}$, where α is weakly redshift dependent but non-trivially mass-dependent with $\alpha \sim 0.2$ for a Milky-Way mass halo at $z = 1$ (i.e. an assumed galaxy mass $5\times10^{10}\,M_{\odot}$). For such a system, as pictured in Figure 1, the galaxy will grow by a fraction $> \delta_0$ in the time t_0 (secular response time) for perturbation amplitudes below

$$\delta_{\rm crit,\ acc} = \frac{\alpha}{(1-\chi_{\rm eff})}\,\frac{P_d}{t_H(z)} \sim \frac{0.003}{1-\chi_{\rm eff}}\,(z=0)\ . \tag{7}$$

Figure 1 considers the "maximally unstable" ($\chi_{\rm eff} = 0$) case, such that $t_0 = P_d$. If the stability parameter is higher (larger t_0), the regime of effective "isolation" will be more restricted. Figure 2 illustrates the parameter space as a function of the effective disk stability parameter $\chi_{\rm eff}$ (recall, this is simply defined relative to the number or orbits needed to grow the mode of interest). Above some critical $\chi_{\rm eff}$ (here $\chi_{\rm eff} \sim 0.75$, i.e. $N_{\rm orbits} = 4$ or $t_0 \gtrsim 0.5\,$Gyr for a MW-like disk), the secular timescale is always longer than the other timescales above. This is simply the statement that disks are not "isolated" for timescales $\gtrsim$ Gyr, especially at high redshift.

3 DEPENDENCE ON GALAXY MASS AND REDSHIFT

Figure 3 shows how the regime of secular evolution depends on galaxy mass and redshift. First, we consider the same comparison at $z = 0$ as a function of galaxy mass. Observations indicate that P_d is nearly mass-independent at the disk effective radii of interest for global models (Bell & de Jong 2001; Shen et al. 2003;

[4] The merger rates from this model as used here can be also obtained as a function of e.g. galaxy mass, mass ratio, and redshift from the "merger rate calculator" script publicly available at `http://www.cfa.harvard.edu/~phopkins/Site/mergercalc.html`

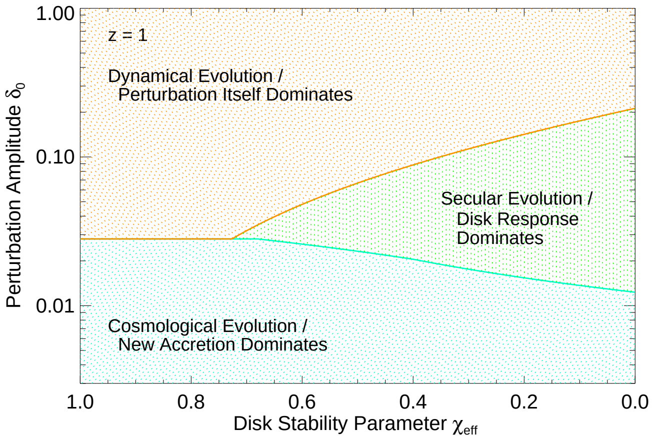

Figure 2. Parameter space of regimes in Figure 1 for the same $\sim L_*$ system as a function of perturbation amplitude and effective disk stability (speed of the growth of secular modes of interest).

Courteau et al. 2007). Given Equation 5, the same is true for dynamical evolution of individual perturbations (at fixed δ_0). However, accretion and merger rates scale significantly with mass. At low masses, merger rates are low, but accretion rates are high. At high masses, accretion rates drop rapidly (consistent with zero at $M_{\rm gal} \gg 10^{11}\,M_{\odot}$), but merger rates increase, leaving almost no range of perturbation in which secular processes are relevant (right column of Figure 3). Both effects are seen in a variety of models and observations (Maller et al. 2006; Noeske et al. 2007; Guo & White 2008; Kitzbichler & White 2008; Parry et al. 2008; Stewart et al. 2008a; Kereš et al. 2009; Bundy et al. 2009). The mass dependence is important even over a relatively narrow mass range – for example, note that our previously assumed Milky-Way like mass of $5\times10^{10}\,M_{\odot}$ (Figure 1), being a factor ~ 2 smaller than the $10^{11}\,M_{\odot}$ case shown here, has correspondingly more rapid accretion rates (between the $10^{10}\,M_{\odot}$ curve and $10^{11}\,M_{\odot}$ curve).

Again, we emphasize that we are using baryonic mass ratio μ here – this is a minimum, as it reflects the most densely bound material that will survive to perturb the galaxy (an individual merger may "begin" at larger δ including dark matter, or smaller δ at large radii, but orbital decay and stripping will tend to saturate it at $\delta\phi/\phi \sim \mu$, with a rate of new such events from mergers as shown; see e.g. Kazantzidis et al. 2008). Low-mass galaxies are observed to be more dark-matter dominated, so if this can be conserved, the relevant rates will not decrease as rapidly with stellar mass; however, modeling this requires more detailed knowledge of cosmological orbits, stripping, and internal galaxy structure.

For each mass, Figure 3 shows how the regime of secular evolution depends on redshift. To lowest order, accretion timescales evolve with the Hubble time (fitting directly, accretion rates $\propto (1+z)^2$; see Stewart et al. 2008a). Observations of the baryonic Tully-Fisher and size mass relation suggest that P_d (or equivalently at fixed mass, disk sizes) evolves weakly from $z = 0-2$ (Trujillo et al. 2006; Flores et al. 2006; Kassin et al. 2007; Toft et al. 2007; Akiyama et al. 2008; Somerville et al. 2008). Moreover, theoretical models that include the well-established dependence of halo concentration on redshift (see e.g. Bullock et al. 2001; Wechsler et al. 2002) predict a similar weak scaling (Somerville et al. 2008). Parameterizing as $P_d \propto (1+z)^{-\beta_d}$, these observations constrain $\beta_d = 0.0-0.6$. In Figure 3, we conservatively adopt $\beta_d = 0$ (i.e. P_d independent of redshift), but we show how the results would change if we allowed the maximum observationally inferred evolution, $\beta_d = 0.6$. It makes a small difference, but does cancel some of the redshift evolution in the relevant parameter space. Even in the extreme case of a simple $P_d \propto t_{\rm Hubble}$ scaling (Mo et al. 1998), some, but not all of the evolution is negated (at $z < 2$, merger and cooling rates evolve as $\propto (1+z)^2$, $1/t_{\rm Hubble}$ as $\propto (1+z)$).

In Figure 3, the critical amplitude below which the "accretion regime" pertains scales *roughly* as $\delta_{\rm crit,\,acc} \propto (1+z)^{1.5-2.0}$, while $\delta_{\rm crit,\,df} \sim$ constant. This is an approximation over the entire range $z = 0-2$; in fact at the lowest redshifts ($z \lesssim 0.2$), the falloff in $\delta_{\rm crit,\,acc}$ is somewhat more rapid (as e.g. the Universe's acceleration term becomes important). As a consequence, the range of δ_0 over which "isolation" is a good approximation decreases with increasing redshift.

Figure 4 summarizes the parameter space as a function of galaxy mass and stability parameter $\chi_{\rm eff}$, at $z = 0$, $z = 1$, and $z = z_{\rm form}(M_{\rm gal})$. We define $z_{\rm form}(M_{\rm gal})$, the galaxy assembly time, as the redshift when each galaxy reaches half its $z = 0$ mass, according to our simple growth model. To the extent that secular modes are considered important in this formation process, this is an interesting timescale.

Simulations find that star-forming galaxies accrete most of their mass along a couple of dynamically coherent, clumpy filaments; as such they are dynamically important for large-scale disk modes (Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Dekel et al. 2009). If, however, accretion were perfectly smooth, axisymmetric, and restricted to large radii (without migration of new material inwards), then it might be valid to ignore it in studying secular modes even when accretion rates are large. To represent this possibility, Figure 5 re-calculates Figure 4, but ignores accretion. At low masses, merger rates are sufficiently low that the isolated regime extends to smaller mass ratios $\delta < 0.01$.

4 IMPLICATIONS FOR MODE "LIFETIMES"

The cosmological evolution of galaxies also has important implications for mode "lifetimes." Since $t_0 = 1/(1-\chi_{\rm eff})\,P_d$, there is clearly some $\chi_{\rm eff}$ at each redshift above which t_0 is larger than any of the competing timescales for *all* δ_0. Modes with larger $\chi_{\rm eff}$ are still formally unstable, but the time/number of orbits to amplify the mode becomes sufficiently long that these modes should be considered cosmologically dynamical objects. Figure 6 shows this maximum $\chi_{\rm eff}$ as a function of redshift (for $\sim 10^{11}\,M_{\odot}$ galaxies where this is maximized, as seen in Figure 4). At $z \gtrsim 1$, this corresponds to modes growing in $\lesssim$ a couple P_d; at $z \geq 2$, however, even $\chi_{\rm eff} = \ll 1$ systems (those where modes grow on a timescale $\sim P_d$) can be in the "accretion regime," as discussed above. Recall, simulations suggest that even cold, bulge-free MW-like disks have effective $\chi_{\rm eff} \sim 0.5-0.75$ (Dubinski et al. 2008, and references therein). This high-z behavior is directly related to observations showing that disk orbital periods at high redshifts become comparable to the Hubble time (see e.g. Flores et al. 2006; Kassin et al. 2007; Toft et al. 2007; van Starkenburg et al. 2008; Shapiro et al. 2008).

At $\chi_{\rm eff}$ less than the values above, secular modes can grow "in isolation" from some δ_0. Typically, these will grow rapidly and saturate at some $\delta_f \sim 1$. However, if an isolated mode then survives stably at an amplitude δ_f for a lifetime much longer than the other timescales compared here, then various cosmological effects may have important consequences. For example, if a disk bar saturates and survives with some $\delta_f \sim 0.4$ (Dubinski et al. 2008), in some number of dynamical times the galaxy will grow by this

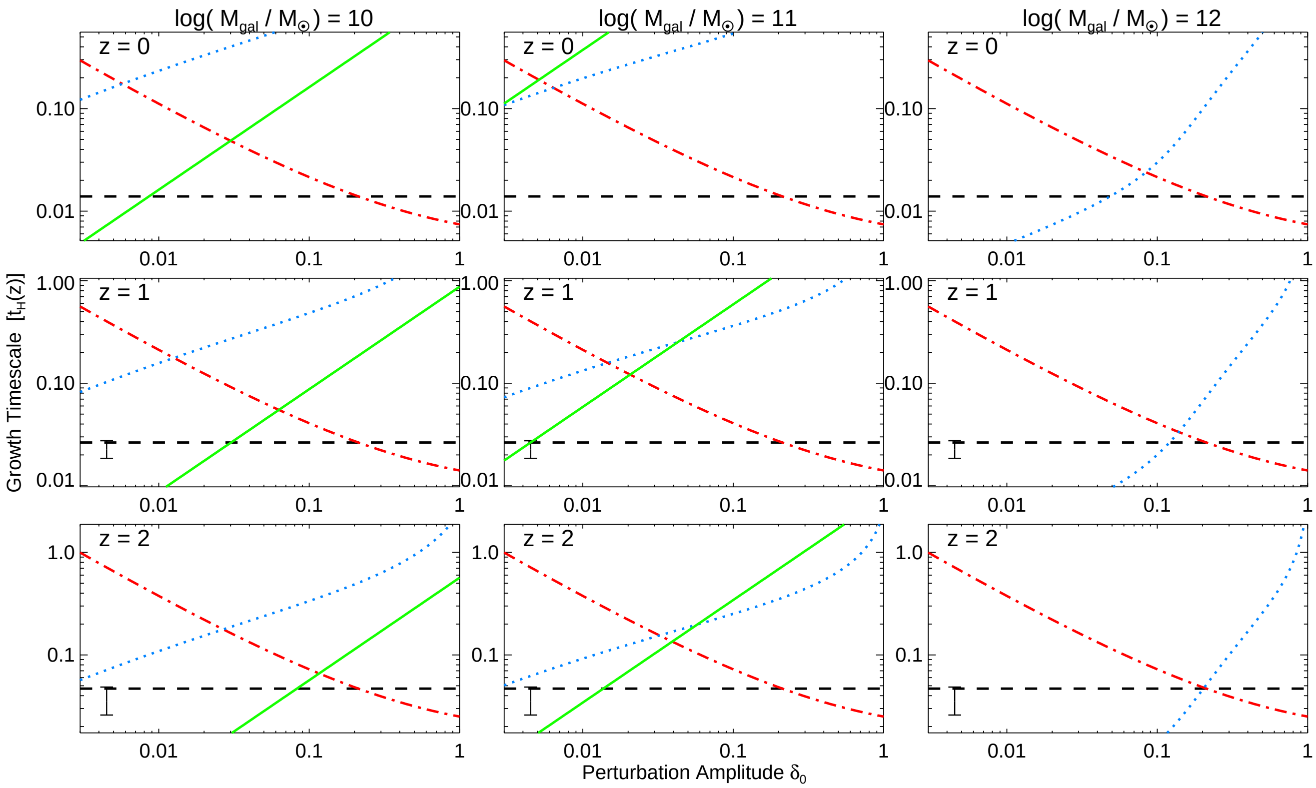

Figure 3. Same as the right panel of Figure 1 ($\chi_{\rm eff}=0$), as a function of galaxy mass and redshift. In low-mass ($\lesssim 10^{10}\,M_{\odot}$; *left*) galaxies, merger rates are low, but accretion rates rapid – secular responses at the $\ll 10\%$ level compete with cosmological disk growth. At intermediate masses $\sim L_{*}$ ($\sim 10^{11}\,M_{\odot}$; *center*) accretion and minor mergers occur with comparable rates. At high masses ($\gtrsim 10^{11}\,M_{\odot}$; *right*) accretion rates are low (cooling is inefficient) but merger rates grow rapidly – secular responses at the $\lesssim 10\%$ level compete with mergers. As a function of redshift, disk dynamical times scale weakly, but merger and accretion rates increase, leaving less of parameter space in which disks can be considered "isolated" for the internal response time. Error bars mark the range between the internal response time if disk sizes do not evolve with redshift ($\beta_d=0$; dashed lines) and if they evolve at the maximum rate constrained by observations ($\beta_d=0.6$; lower bar).

much. Essentially, cosmological growth may "catch up" to the saturated mode and could effect it. Of course, the mode could continue growing with the galaxy, or be robust to these effects; our point is that continuing to treat such a mode in isolation may not necessarily be a good approximation over much longer timescales. Moreover, if stable modes can survive for a timescale much longer than e.g. the relevant dynamical friction times at δ_0, then the *presence* of those modes mode (the duty cycle) will de-couple from that of their drivers (if they were initially driven). In e.g. the case of minor mergers, this is the statement that new mergers and/or the destruction of the original driving satellites will wipe out the "memory" of the drivers, while the bar survives.

Taking the minimum of the non-secular timescales of interest (e.g. accretion and merger timescales in Figure 3) at whatever amplitude δ maximizes this timescale, gives the maximum relevant "isolated" mode lifetime. This is clearly a function of mass; we consider here the $\sim 10^{11}\,M_{\odot}$ ($\sim L_{*}$) case, of greatest interest both as a MW-like system and because Figure 4 demonstrates that this is where such a timescale (the "isolated" regime) is maximized. Figure 7 plots this timescale versus redshift. We show this both for the assumption that P_d does not evolve ($\beta_d=0$) and the maximum observationally constrained evolution ($\beta_d=0.6$). We compare a constant fraction (~ 0.1) of the Hubble time – this appears to be a good approximation, on average (there will of course be scatter galaxy-to-galaxy in accretion and merger rates, leading to typical factor ~ 2 scatter in the relevant timescale here).

5 DISCUSSION

Under typical cosmological conditions, global "secular" evolution – narrowly defined as evolution by internal amplification of large-scale disk modes in effectively *isolated* galaxies – only occurs in a restricted range of parameter space (Figures 1-2). If the perturbation mode of interest has a fractional amplitude $\ll 0.1$, what we call the "accretion regime," then the disk will grow by accretion by a comparable amount in even a single dynamical time; the isolated approximation is clearly not valid. This threshold is around an amplitude $\delta_{\rm crit,\,acc}\sim 0.002\,(1-\chi_{\rm eff})^{-1}\,(1+z)^{1.5-2}$ for $10^{11}\,M_{\odot}$ galaxies (slightly lower at $z<0.2$) or $\delta_{\rm crit,\,acc}\sim 0.005\,(1-\chi_{\rm eff})^{-1}\,(1+z)^{1.5-2}$ for $10^{10}\,M_{\odot}$ systems. At the opposite extreme, seed "perturbations" of fractional amplitude $\delta_0>\delta_{\rm crit,\,df}\sim 0.2$ lead to non-secular evolution – the perturbations' own gravitational evolution will dominate the internal response (this is obvious in the case of e.g. galaxy-galaxy major mergers or massive disk fragmentation events, where the evolution of the merger/clumps drives violent relaxation).

The relevant parameter space depends on galaxy mass (Figures 3-5). Although halo growth is nearly mass-independent (Fakhouri & Ma 2008; Guo & White 2008; Stewart et al. 2008a), galaxy growth histories are not (the function $M_{\rm gal}(M_{\rm halo})$ is non-trivial). At high masses ($M_{\rm gal}\gtrsim 10^{11}\,M_{\odot}$) galaxy-galaxy merger rates are high such that systems are rarely "isolated" over the timescales of interest for secular evolution. However, there are few disks at these masses, so secular evolution is not expected to be

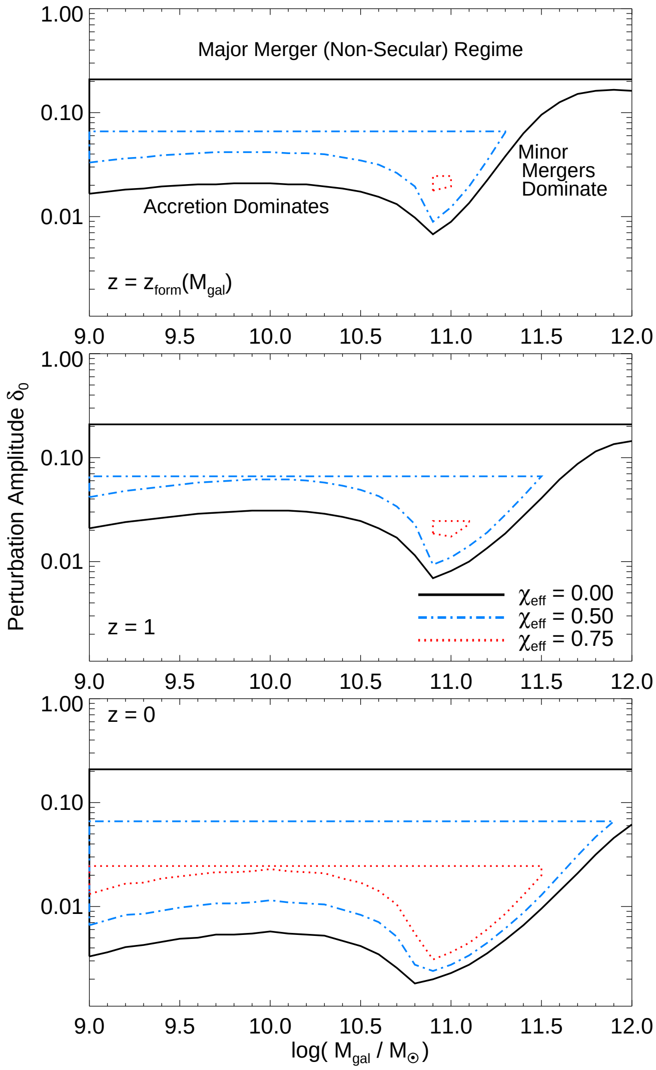

Figure 4. Parameter space of the "isolated" secular regime (Figure 1) versus galaxy mass and $\chi_{\rm eff}$, for a redshift-independent disk period P_d. *Top:* At the formation redshift $z = z_{\rm form}$, where each galaxy reaches half its $z = 0$ mass. *Middle:* At $z = 1$. *Bottom:* At $z = 0$.

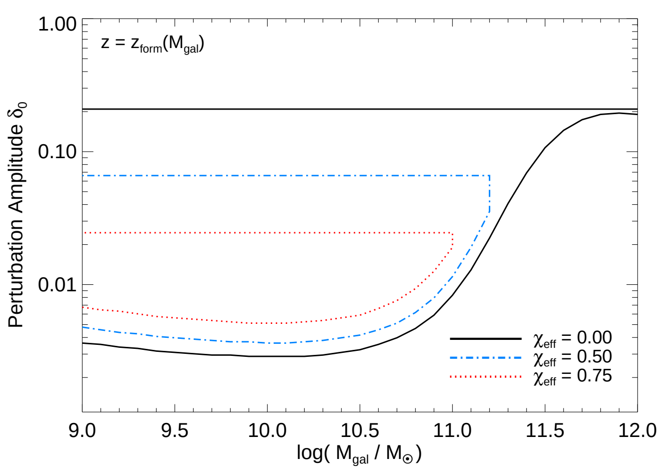

Figure 5. As Figure 4 (with $z = z_{\rm form}$); but neglecting cosmological accretion (i.e. considering only merger timescales as the competing timescale at low-δ).

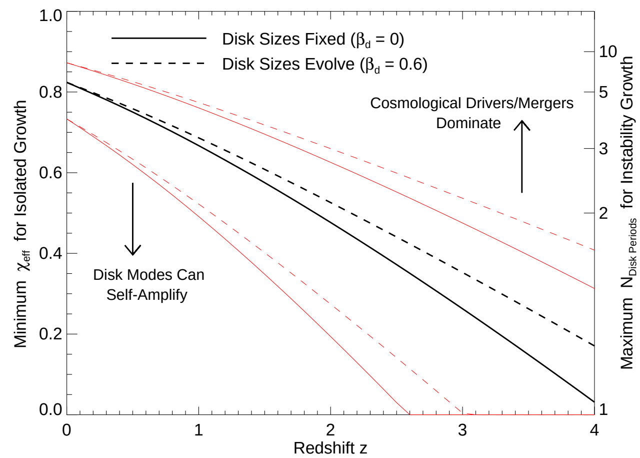

Figure 6. Minimum effective stability parameter $\chi_{\rm eff}$ or maximum $N_{\rm Disk\ Periods} \equiv 1/(1-\chi_{\rm eff})$ where the secular growth timescale equals the maximum isolated lifetime in Figure 7. Black (red) lines show the median ($16-84\%$ range) expected. In more stable (slower-responding) disks, large-scale modes should be considered cosmologically dynamical systems.

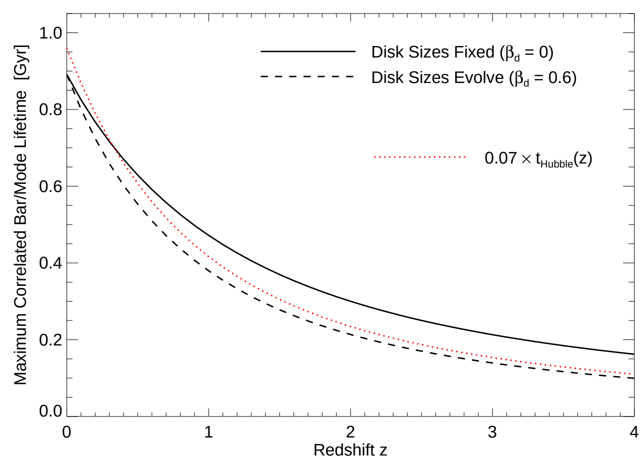

Figure 7. The maximum "isolated" lifetime of large-scale modes (e.g. disk bars). This is the largest timescale (marginalizing over δ and $M_{\rm gal}$) shorter than the competing (non-secular) timescales in e.g. Figure 3. Variations within populations contribute factor ~ 2 scatter from object-to-object. We show a fixed fraction of the Hubble time for comparison. Evolution on longer timescales will compete with cosmological effects. The duty cycle will de-couple from driving: even if all such modes were driven by e.g. minor mergers, there will be no correlation between the presence of the modes and the presence of companions.

a dominant process. At low masses ($\lesssim 10^{10}\,M_{\odot}$) merger rates are low (in terms of galaxy-galaxy baryonic mass ratios; including dark matter, they may remain high) but accretion rates are high; systems can be effectively approximated as isolated for only a couple of orbits in the regime of amplitudes $\delta \sim 0.03-0.2$. Moreover, although such galaxies are mostly disk ($B/T \ll 1$), they are increasingly dark matter-dominated which helps stabilize them to the development of secular modes (see e.g. Persic et al. 1996; Mihos et al. 1997; Borriello & Salucci 2001; Bell & de Jong 2001). Galaxies may be "most isolated," and so traditional secular evolution most relevant, between these regimes, i.e. in galaxies somewhat below $\sim L_*$. That this occurs at masses only somewhat below where mergers become efficient is also interesting; there may be a relatively

rapid regime (as galaxies approach and cross $\sim L_*$ in mass) in which today's galaxies transition from accretion-dominated, secularly stable (dark matter-dominated) disks, to secularly unstable (self-gravitating) disks, which could quickly amplify $\sim 10\%$ amplitude perturbations into very strong bars and build significant pseudobulges, until later mergers destroy the remains of the disk and build massive classical bulges.

This has important implications for the lifetimes of secular processes of interest. The above comparisons assume disks where the internal response occurs over a single orbital period; if the systems have higher effective stability (i.e. secular responses build more slowly), then the regime where they can be considered isolated for this time shrinks. Large-scale modes that require more than a few disk periods to self-amplify at low-redshift, or more than just a single disk period at high redshift ($z > 2$), should be considered cosmologically dynamical systems (Figure 6) – the galaxy grows comparably over this self-amplification timescale. Indeed, various observations of disk sizes and structure suggest that disks are sufficiently thick or have sufficient bulge fractions such that internal response times are in this interesting range (Bell & de Jong 2001; McGaugh 2005; Courteau et al. 2007; Gilmore et al. 2002; Wyse et al. 2006; Barteldrees & Dettmar 1994; de Grijs et al. 1997).

Even if modes can evolve/self-amplify quickly such that a bar will grow efficiently and saturate at some final amplitude, these competing timescales define a maximum "isolated" lifetime for that saturated mode that is of interest, $\sim 0.1\,t_{\rm Hubble}$ (Figure 7). There has been substantial debate regarding the lifetime of stellar bars in disks; but if modes live stably in isolation for longer than this time, they will encounter significant cosmological effects including e.g. significant new disk growth and mergers. Indeed, most studies do agree that lifetimes in isolation are at least this long (see e.g. Weinberg 1985; Hernquist & Weinberg 1992b; Friedli et al. 1994; Athanassoula 2002a; Kaufmann et al. 2007). Evolution of modes on longer timescales (e.g. some self-damping or buckling processes) should ideally be considered in a live cosmological context – the time in isolation may strengthen modes against external effects, but various studies have found that a moderate level of new gas accretion or passages of new substructure can dramatically change mode evolution, both exciting and destroying bars and spiral waves (see Athanassoula et al. 2005; Bournaud & Combes 2002; Berentzen et al. 2003, 2004, 2007; Foyle et al. 2008); not to mention that the presence of pre-existing strong bars may in turn affect these accretion/merger processes.

Moreover, if modes live this long, their duty cycles will decouple from those of their drivers. Even if, for example, all large-scale bars were initially driven by encounters with satellite galaxies (minor interactions), if the isolated lifetime were much longer than this value, there would be no surviving correlation between the *presence* of bars and such companions. There has been considerable observational debate regarding whether or not strongly-barred galaxies exhibit any strong preference for minor companions; certainly there are at least many such galaxies without close neighbors (see Elmegreen et al. 1990; Odewahn 1994; Moles et al. 1995; Marquez & Moles 1996; Li et al. 2009, and references therein). This may in fact be because strong bars are not driven; however, it could also be consistent with the hypothesis that all such bars were initially driven, but are sufficiently long-lived. Constraints on bar lifetimes are needed to break the degeneracies.

The level of cosmological dynamics also has implications for the numerical considerations involved in simulations of "isolated" systems. Properly following resonant self-interactions of bars may imply steep resolution requirements in N-body experiments (see e.g. Weinberg & Katz 2007a,b; Ceverino & Klypin 2007; Sellwood 2008). However, there are other properties for which increasing the resolution in idealized cases may not be a more accurate representation of reality. In terms of shot noise in the potential, for example, a model MW-like disk with $\gg 10^6$ particles will have potential fluctuations from smooth axisymmetry $\delta\phi/\phi \lesssim 1\%$ over the spatial/timescales of interest (disk size and dynamical time). In cosmological simulations, although the central regions of halos are relatively smooth, even dark-matter only simulations yield comparable or larger variations in the local potential/velocity dispersion at e.g. MW-like disk effective radii (see Zemp et al. 2008). Even where smooth in space, such systems are not constant in time (as in idealized cases) at this level over several dynamical times. Moreover inclusion of baryons (which are not stripped efficiently, unlike dark matter subhalos which are efficiently destroyed at small radii and so do not "survive" to contribute substructure inside the centers of halos) enhances the clumpy, minor spatial substructure. In the Milky Way, for example, the LMC-SMC system represents a real deviation from a smooth, axisymmetric potential at a level larger than this limit near the solar radius. Ideally, tracking the evolution of substructure at higher resolution should involve not just a larger number of particles, but cosmologically motivated descriptions of substructure and accretion.

Interestingly, at all redshifts, we find that traditional isolated "secular" evolution is most applicable around perturbations of fractional amplitude $\sim 10\%$. This is a very interesting regime of parameter space: to the extent that it represents a fractional amplitude of substructure/accretion flows, it is a channel by which halos and low-mass galaxies gain much of their mass (e.g. Governato et al. 2007; Kazantzidis et al. 2008; Stewart et al. 2008b). Moreover, "pseudobulges," associated with bulge formation from secular evolution (e.g. bar-induced inflows and bar buckling; see e.g. O'Neill & Dubinski 2003; Mayer & Wadsley 2004; Debattista et al. 2004; Athanassoula 2005, and references therein) appear to dominate the bulge population at mass ratios of similar amplitude ($B/T \lesssim 0.1-0.2$; see Kuijken & Merrifield 1995; Jogee et al. 2004; Kormendy & Kennicutt 2004; Fisher 2006; Fisher & Drory 2008; Weinzirl et al. 2009). Suggestively, this also corresponds to typical amplitudes of observed strong bars (references above and Eskridge et al. 2000; Laurikainen et al. 2002; Sheth et al. 2003; Marinova & Jogee 2007; Barazza et al. 2009).

Of course, real systems exhibit more complex behavior then the simple scalings we derive here. Ultimately, detailed progress in modeling the interplay between continuous accretion of new substructure and cosmological driving of perturbations coupled to non-linear modes in galactic disks will require high-resolution *N*-body and hydrodynamic cosmological simulations. Some progress has begun towards modeling these processes in a proper cosmological context (see e.g. Bournaud & Combes 2002; Gauthier et al. 2006; Berentzen & Shlosman 2006; Kaufmann et al. 2007; Governato et al. 2007; Foyle et al. 2008; Kazantzidis et al. 2008; Romano-Diaz et al. 2008) – these studies highlight a key point here, that in a large regime of parameter space it is difficult to disentangle "secular" and cosmological processes. Our goal here is not to derive a rigorous quantitative description of one or the other. However, the simple arguments here should help to constrain and focus the discussion of where and when (in realistic cosmological settings) "isolated" evolution is important.

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